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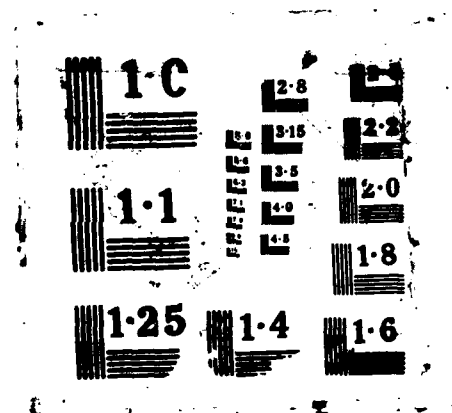
STRENGTH AND BEHAVIOR OF STEEL FIBER-REINFORCED
CONCRETE AND SOIL STRUCTU. (U) COLORADO UNIV AT BOULDER
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<p>→ This report summarizes two phases of the research project. The first phase dealt with the strength and behavior of steel fiber reinforced concrete subjected to biaxial compression-tension loadings. A new piece of direct tension loading apparatus was designed and assembled for this study. Load history effects on the degradation of the tensile strength were also investigated.</p> <p>The second dealt with the modeling of a buried culvert system, both numerically and in the geotechnical centrifuge. The centrifuge test results were compared to the numerical analytical results to provide a validation of the numerical algorithm in which constitutive models could be incorporated. ←</p>					
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FINAL REPORT TO THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
ON GRANT NO. AFOSR-81-0072

"STRENGTH AND BEHAVIOR OF STEEL FIBER-REINFORCED CONCRETE
AND SOIL STRUCTURES INTERACTION STUDIES"

FOR PERIOD JANUARY 15, 1981 TO AUGUST 31, 1984

by

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This research project was originally begun to follow up on a previous investigation of the constitutive properties of steel fiber reinforced concrete (SFRC) under multiaxial compressive loading conditions that was conducted under AFOSR Grant No. 79-0065. The first primary goal of this project was to develop techniques for testing SFRC under *combined* compression-tension loadings which are certainly the predominant mode of loading found in all concrete structures, particularly those that are used as protective structures for strategic weapons systems. It was deemed important to develop the capability of testing SFRC materials under direct, combined compression-tension loading. Considerable efforts were devoted to the design and fabrication of a direct tension loading apparatus that can be attached to the existing multiaxial cubical (compressive) test cell in order that such combined loading tests could be performed. After this apparatus had been successfully checked out, an extensive test program was conducted to investigate the behavior of SFRC under combined loadings, as well as to ascertain the load history effects on such materials.

The investigation of load history effects was the focus of the second half of the project funded by AFOSR Grant No. 81-0072, during which a secondary objective was also pursued. This second objective was developed in recognition of the fact that in buried structures the influence of the soil medium is as important as the structural material itself. In pursuit of this second objective, the research efforts were focused on using the geotechnical centrifuge as the vehicle for performing physical tests on models of buried structures, using the gravity loading in the centrifuge to simulate the gravity induced stresses in the soil in order to provide similarity in the stress conditions between the model and the prototype being modeled.

The results of both parts of the research project have been reported in graduate theses as well as to the professional community. The list at the end of this report

STEEL FIBER REINFORCED CONCRETE

This direction tension loading apparatus can be used by itself for uniaxial tension testing, or in conjunction with the fluid cushion system in the multiaxial test cell for combined compression and tension loading experiments. For this project, only one axis of tension loading capability was available, but the concept of using brush platens for applying tensile stresses is easily extendable to two or even three axes. With all three axes equipped with tension loading capability, it would then be possible to explore the complete compression-tension stress space in determining the constitutive behavior of the test material.

In the experiments where the loading sequence was monotonic and consisted of first applying a compression to a certain proportion of the unconfined compressive strength of the SFRC, followed by tension loading in a transverse direction until failure was obtained, the results can be interpreted in terms of the biaxial strength as well as the stress-strain response in all three principal directions of the specimen. In Fig. 2, the biaxial compression-tension failure envelope of SFRC is presented. It can be seen from the data in this figure that there is an inflection point in the envelope around a stress level between 40% and 50% of the unconfined compressive strength f_{cu} . The strain responses in the three principal stress directions resulting from the applied tensile stress are shown in Figs. 3 through

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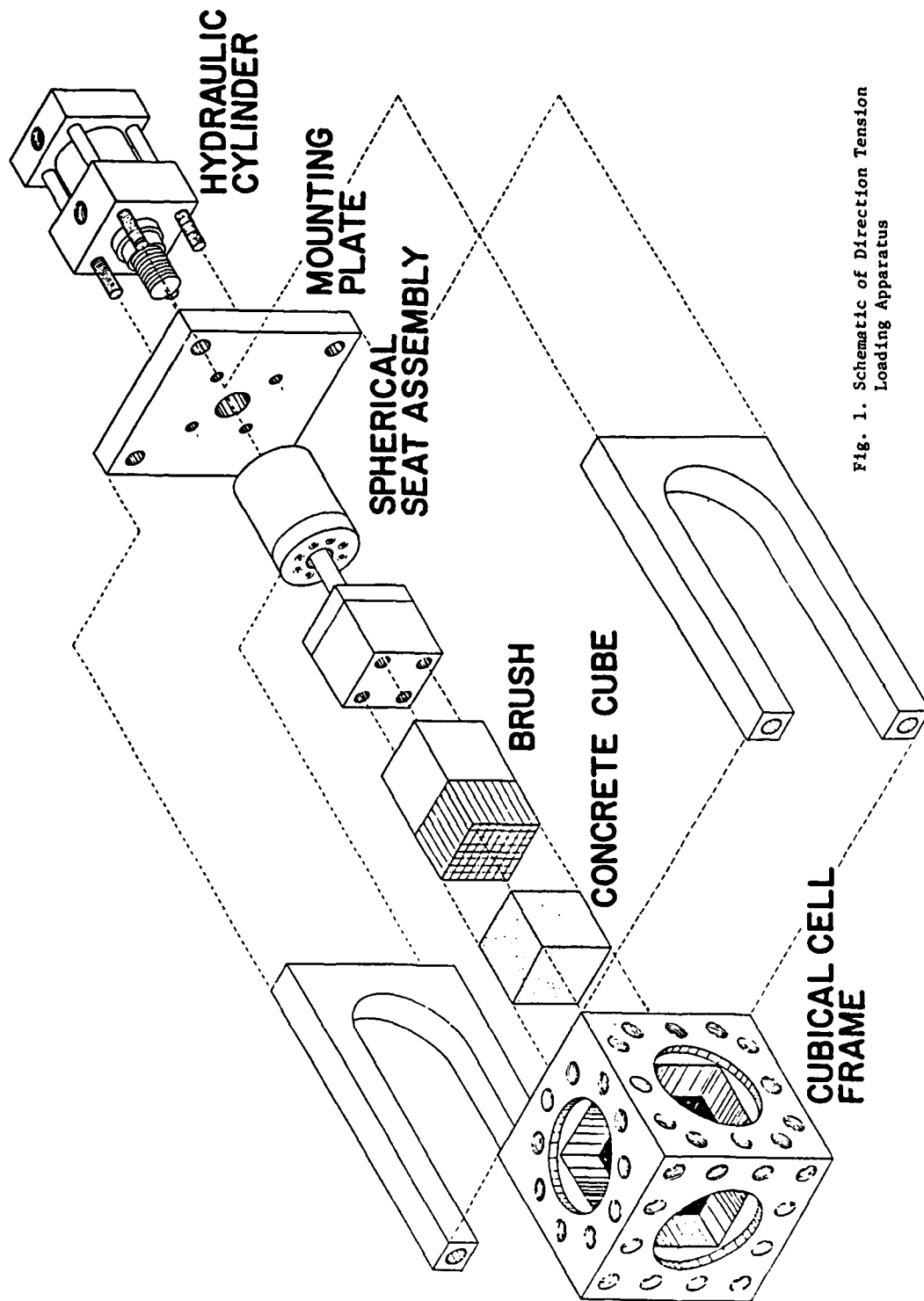


Fig. 1. Schematic of Direction Tension Loading Apparatus

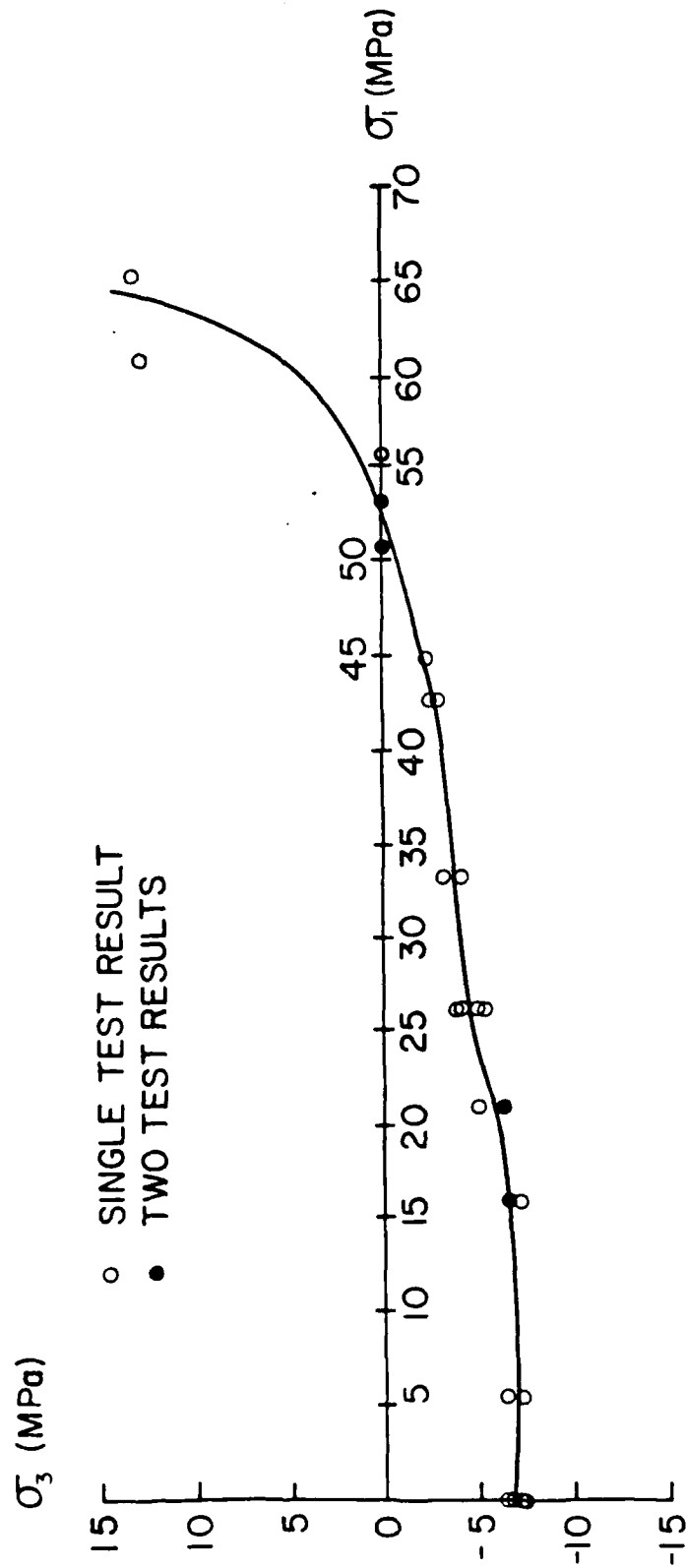


Fig. 2. Strength Results of SFRC in the Biaxial Tension-Compression Region of the Biaxial Stress Plane.

5. In these figures, the number shown with each individual curve denotes the amount of compressive loading relative to f_{cu} . Fig. 3 shows the tensile strain response to the tensile loading. The increased softening and weakening of the concrete with increasing compressive loading are indicative of the amount of internal damage sustained. Furthermore, the ductility of the material increases as the strain to ultimate strength increases. Similar features are observed in Fig. 4 where the corresponding compressive strain responses are shown. In both of Figs. 3 and 4, a pronounced change in behavior is observed at a stress level of 0.4 to 0.5 f_{cu} . In this region there is considerable irregularity in the stress-strain response that may be attributed to a transition from brittle tensile fracture to ductile shear failure.

Fig. 5, which shows the strain responses in the direction of the unstressed axis of the test specimen, confirms the existence of such a transition. At the lower precompression levels, a contractive response is observed that coincides with a predominantly tensile mode of failure. At a stress level between 0.45 and 0.5 f_{cu} , a reversal in the strain response to that of expansion takes place, which suggests a cleavage mode of failure in which the microcracks propagate along many planes parallel to the direction of the applied compressive stress.

The point of transition between the two different strain responses coincides with the inflection point in the failure envelope noted previously. The loss of strength over this transition region may be attributed to the initiation of significant crack propagation as a result of the compressive loading. Because these cracks propagate in planes perpendicular to the applied tensile stress, the cross-sectional area of the intact material available for resisting the tensile force decreases rapidly resulting in a drastic increase in localized tensile stresses that quickly approach the tensile strength of the material.

It should be noted that the apparent increase in tensile strength that results from small amounts of compressive loading in the transverse direction can be attributed to the interaction between the steel fibers and the concrete matrix in which they are embedded. The applied compressive stress increases the confinement and frictional resistance of the fibers, thus enhancing their ability to retard crack propagation and increasing the tensile strength of the composite material over that which is measured in uniaxial tension. Likewise, the pronounced loss of strength in the transition region is due in part to the loss of this reinforcing ability as cracks propagate along fiber-matrix interfaces and disrupt the bonds between the fibers and the cement. It is therefore suggested that the inflection in

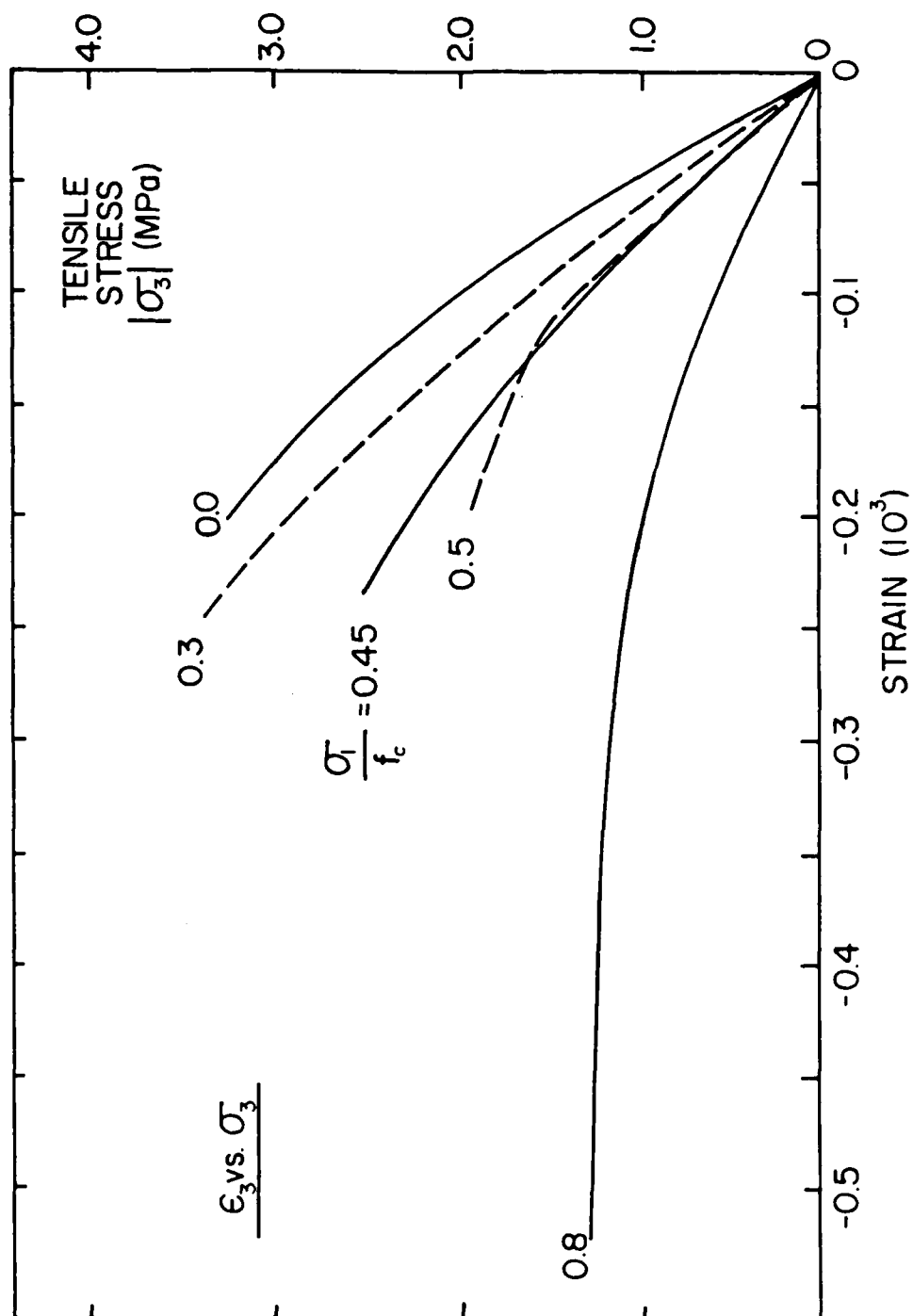


Fig. 3. Stress-Strain Response of SFRC in the Direction of the Applied Tensile Stress.

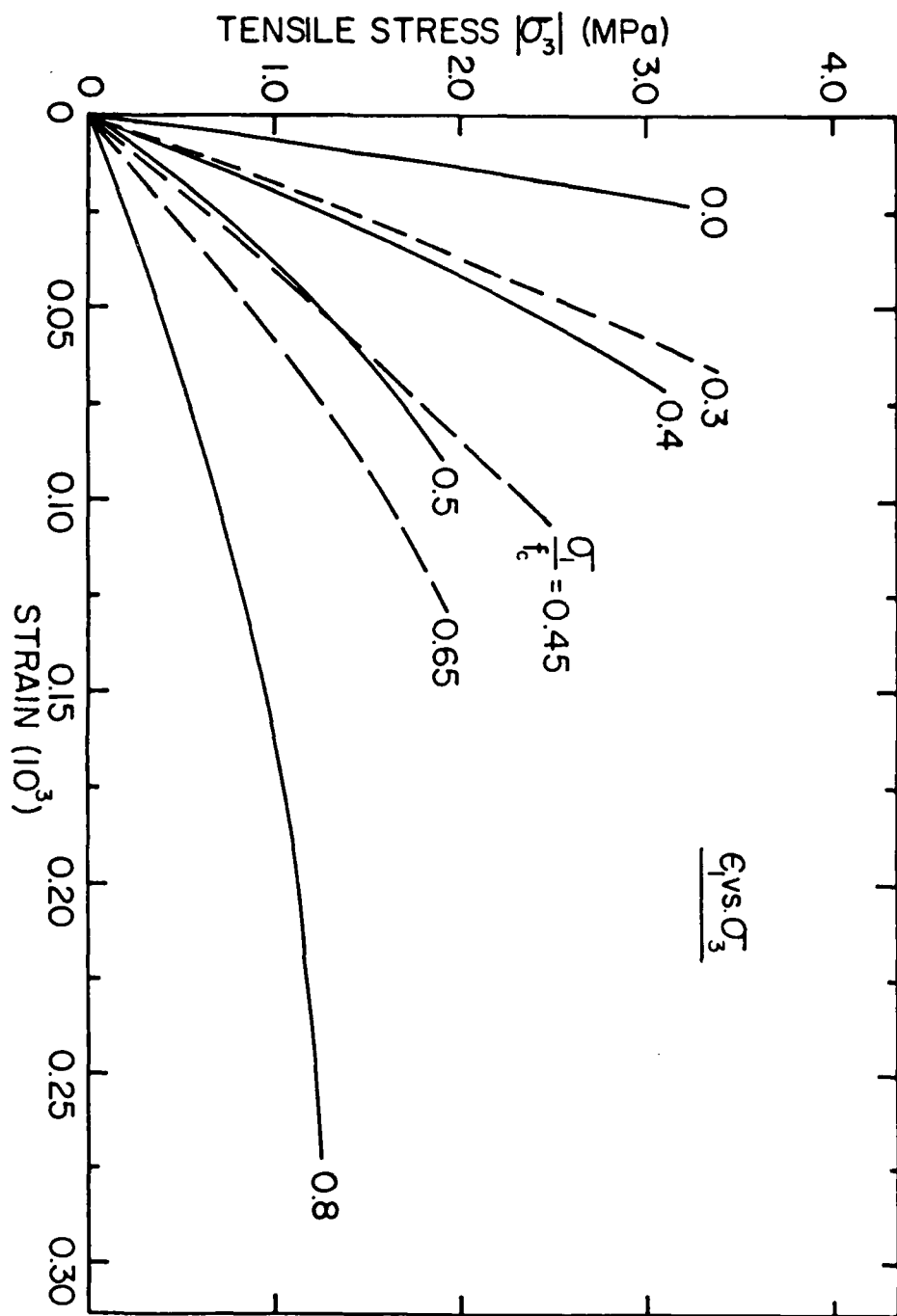


Fig. 4. Stress-Strain Response of SFRC in the Direction of the Applied Compressive Stress.

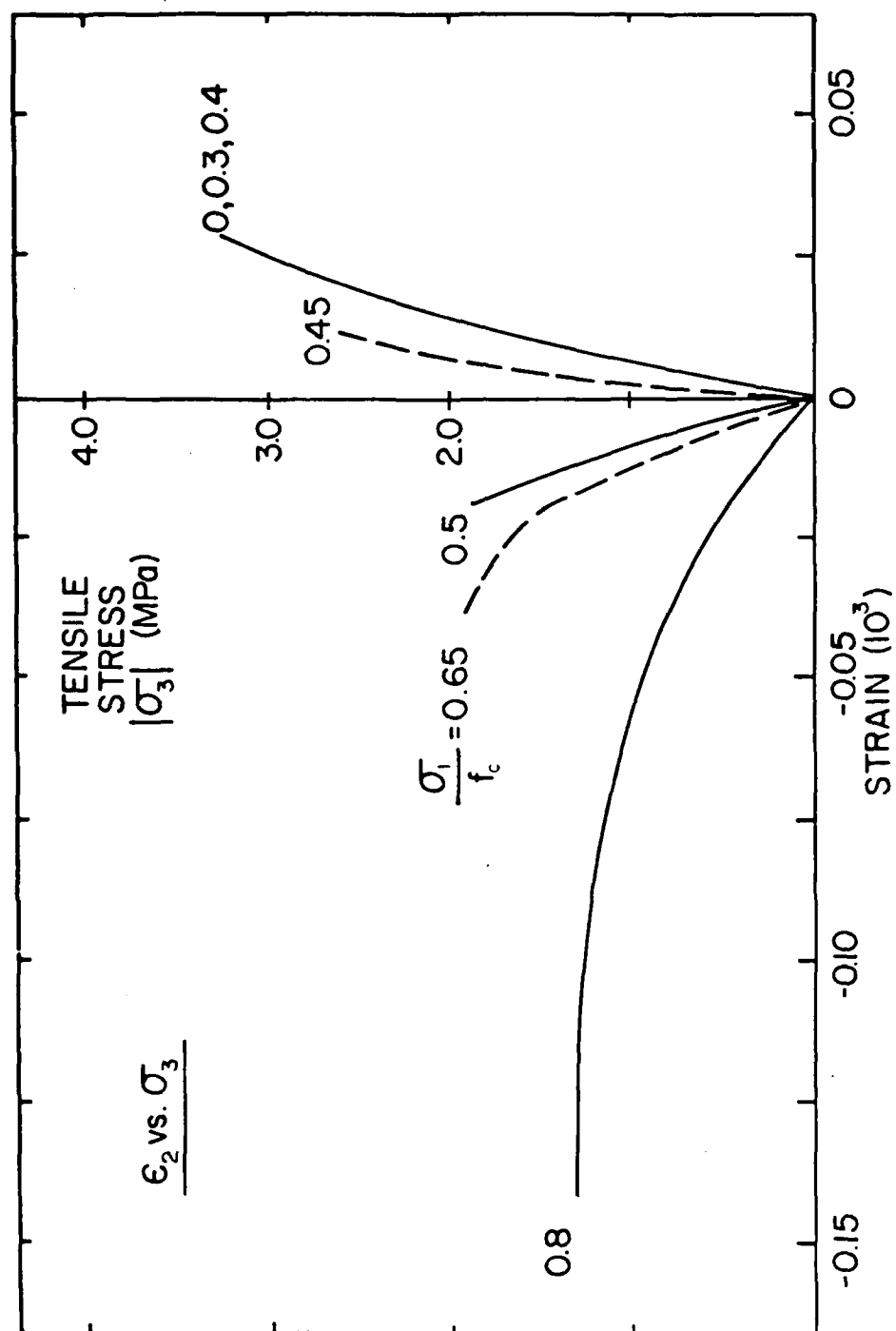


Fig. 5. Stres-Strain Response of AFRC in the Direction of the Unstressed Specimen Axis.

the strength envelope would be much less apparent in the testing of unreinforced materials, such as plain concrete and rocks, although it would still be present to some degree because of the reasons previously mentioned.

A second test program was carried out to investigate the effects of compressive loading histories on the tensile strength of SFRC. It was found that significant degradation of the tensile strength was obtained from such reloading. Some of the results are described next.

Specimens were preloaded along biaxial proportional compressive stress paths to different levels corresponding to 50%, 75% and 85% of the respective virgin biaxial strengths along the stress paths with biaxial stress ratios of 1/3, 2/3 and 1. These preloaded specimens were then tested for their uniaxial tensile strengths in different directions. The direction of tensile testing was coincident with either the intermediate principal stress or the unloaded direction during preloading. These choices were made on the basis of previous experience with compressive loading which showed degradation of concrete developing with microcracks parallel to the direction of the applied major compressive stress.

The results are shown on a normalized basis with respect to the virgin uniaxial tensile and compressive strengths in order to eliminate variations arising from the mix proportions of different batches of the SFRC. The normalized results are shown in Figs. 6 and 7, in which the degraded tensile strength ratio is shown as a function of the compressive preloading ratio. Fig. 6 shows that degradation in tensile strength in the direction of the intermediate principal preloading stress is minimal for compressive preloading up to 85% of the compressive strength. On the other hand, if the degraded tensile strength was measured in the direction previously unloaded during preloading, the results in Fig. 7 show that there is significant degradation. Moreover, there is considerable difference in the effects produced by preloading along different biaxial stress paths, with the most degradation arising from the equal biaxial loading case. This is the obvious result of producing cracking from both directions of the compressive preloading.

SOIL STRUCTURE INTERACTION

A buried culvert depends primarily on the surrounding soil for support, and the structural stresses and deflections are controlled by the interaction between the structure and the backfill. The analysis of such a buried structure system requires the material properties of the soil as well as the structural components. A major

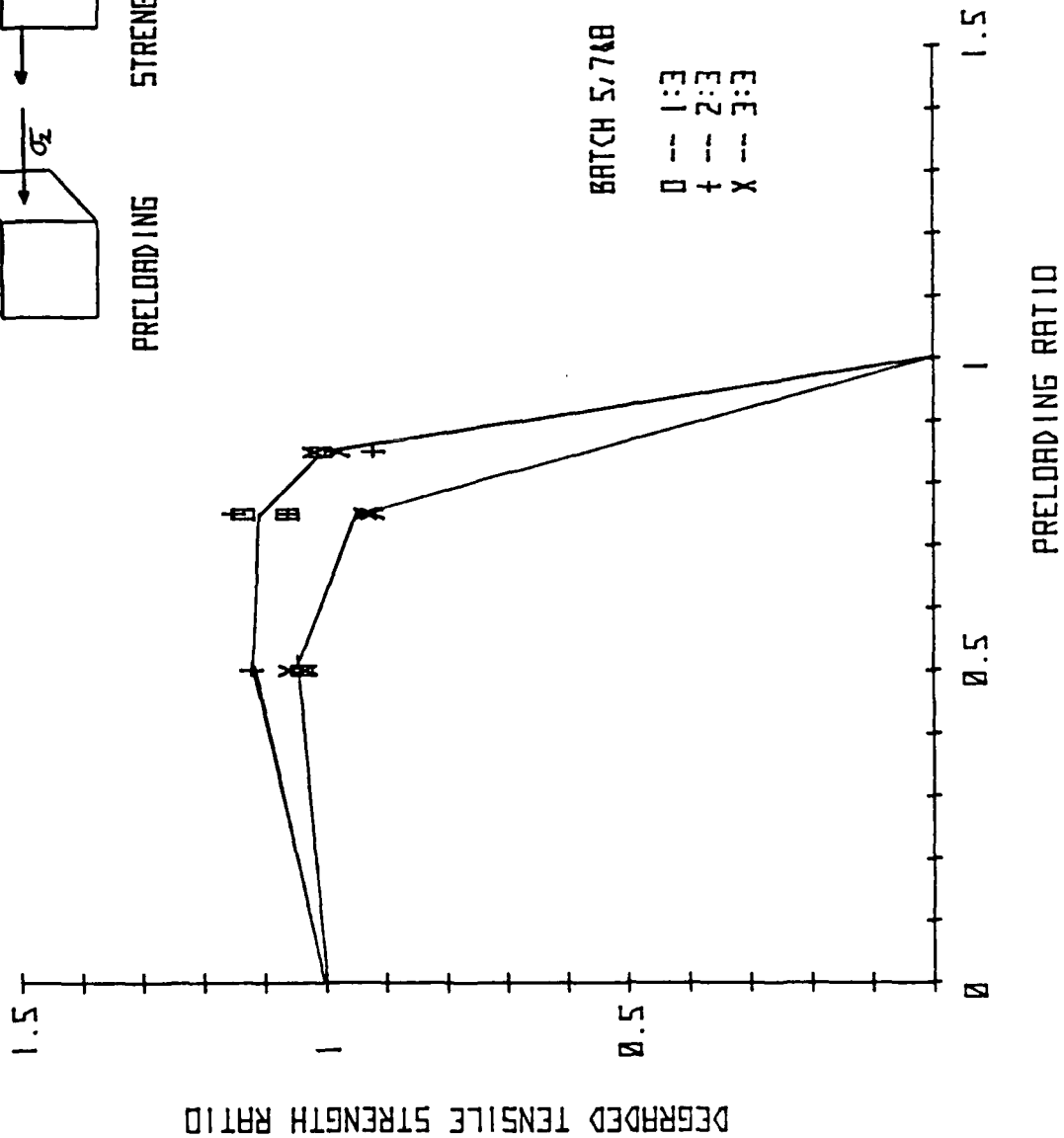
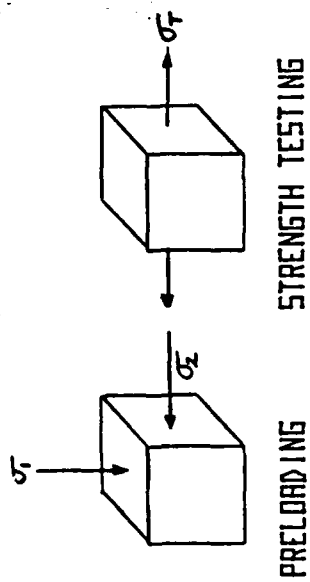


Fig. 6. Degradation of Tensile Strength of SFRC due to Compressive Preloading.

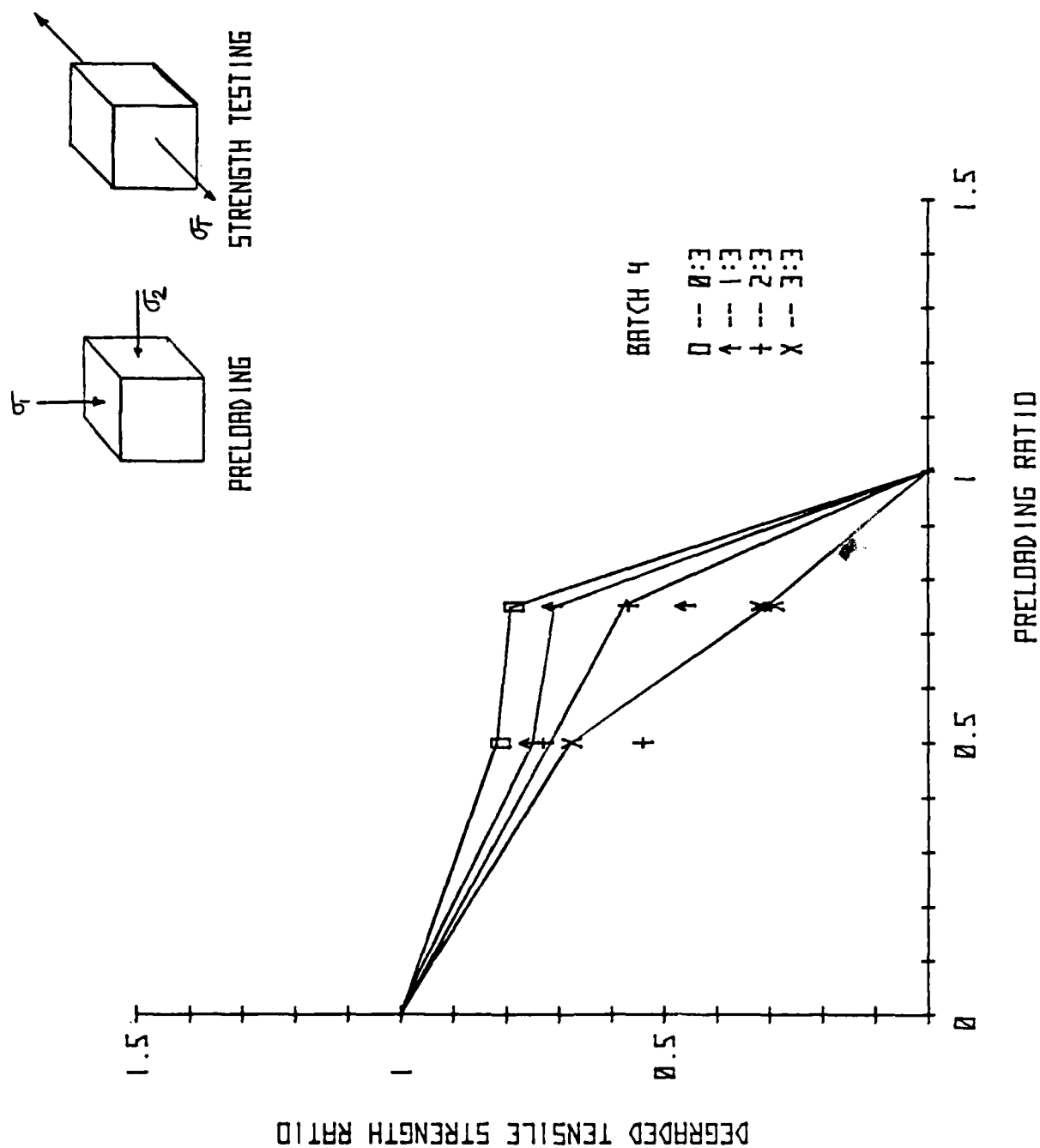


Fig. 7. Degradation of Tensile Strength of SFRC due to Compressive Preloading.

uncertainty is the interaction stresses that control the deflections of the culvert.

The buried culvert system was physically modeled in the geotechnical centrifuge in which the gravity induced stresses in the soil are simulated, which in turn govern the stiffness of the soil. The same system was also modeled numerically with a finite element program developed for this purpose, in which several constitutive models were available for representing the soil's mechanical behavior. By comparing the analytical results with the centrifuge test data, it was possible to draw conclusions regarding the suitability of these constitutive models for soil under the loading conditions pertinent to buried structures.

The buried conduit tested in the centrifuge was a 4-in. diameter aluminum tube with a wall thickness of 0.025 in. and buried with its center at a depth equal to one diameter. All experiments were carried out at 50 g in the 10 g-ton geotechnical centrifuge at the University of Colorado. Therefore, the prototype being modeled would be 50 times larger in all length dimensions. Special techniques were developed for preparing the soil bed and for placing the culvert in the bed to insure proper contact between the pipe and the soil. The model culvert was instrumented with strain gages around the circumference for measuring the bending stresses and the hoop stresses. In addition, miniature LVDT's were mounted on a stiff rod running along the length of the buried pipe on its inside, and the cores of these LVDT's were spring loaded against the inside of the pipe to detect the deflections of the pipe. When the experimental package was accelerated to 50 g in the centrifuge, pressures were applied on the surface of the soil bed both symmetrically and asymmetrically along the length of the pipe. The pipe stresses and deflections were measured at every pressure increment.

The soil used in this study was a silty sand. It was tested in the laboratory to provide data for the calibration of the constitutive models used in the analytical study. A hyperbolic elastic model and Lade's elasto-plastic model were employed.

The numerical algorithm simulated both the gravity loading experienced by the soil during spin-up of the centrifuge as well as during surface loading. The former was deemed important as the gravity induced stresses are influential in determining the soil stiffness. Also several methods of integration of the finite method approximation were attempted.

Fig. 8 shows the results of one centrifuge experiment in terms of the crown deflection as function of the applied

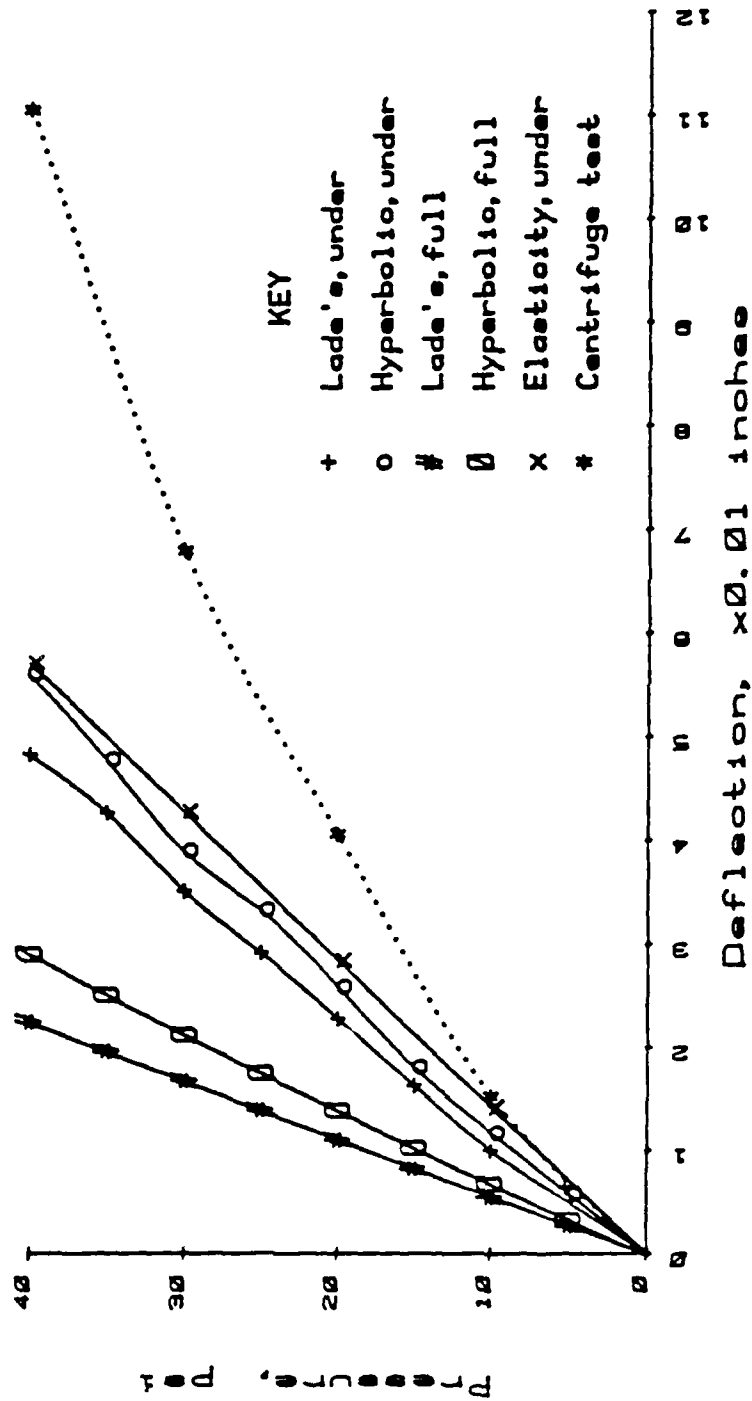


Fig. 8. Deflections at Crown of Buried Culvert --- Comparison Between Under- and Full-Integration In Finite Element Analysis.

surface pressure. Here, the experimental data is compared with the analytical results obtained by using different constitutive relations to represent the soil behavior in the analysis and by using different integration schemes. Likewise, Fig. 9 shows the comparison of the invert deflection from the same test, while Fig. 10 shows deflection profile around the culvert. The comparisons in Figs. 8 and 9 show that the deflections are underpredicted by all the analytical results. It was necessary to use under-integration on the elements representing the culvert in order to avoid the shear locking effect, while full-integration was employed on the soil elements. With this scheme, the results are improved.

The experimental results appear to be better predicted with using the hyperbolic constitutive model than Lade's elasto-plastic model. The reasons for this are two-fold. First, in Lade's model there are two types of yield surfaces, the collapsive yield cap that is associated with the strain hardening arising from volumetric compaction, and the expansive yield surface associated with shear failure. Only the first type was activated in the analysis of the loading of the buried culvert. Because Lade's model is essentially an isotropic model, and since the soil exhibited considerable anisotropy due to the method of compaction, the volumetric strains produced by the activation of the collapsive yield surface under-predicted the actual values. Second, the principal stress directions in the soil show considerable rotation during loading, but the constitutive model did not provide for these effects. Because of the anisotropy in the soil, this deficiency became significant. The same comments are also appropriate for the hyperbolic model. However, it appears that the hyperbolic model is simpler to calibrate and easier to use and adjust. Hence, until the more sophisticated elasto-plastic models, such as Lade's, have incorporated additional features that mitigate the above criticisms, it will be prudent to continue the simpler approach by using the nonlinear elastic hyperbolic model in the analysis of buried culverts.

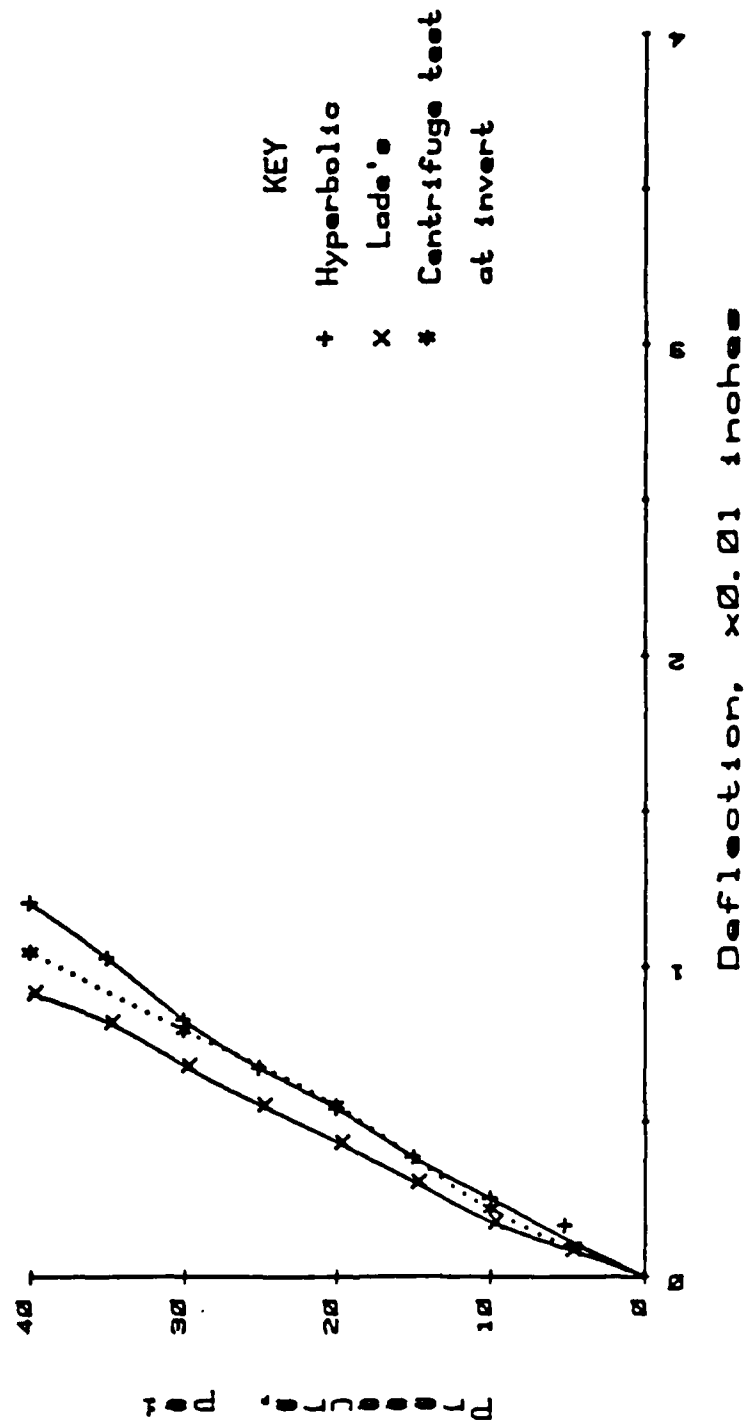


Fig. 9. Deflections at Invert of Buried Culvert -- Comparison Between Analysis Using Different Constitutive Models for Soil.

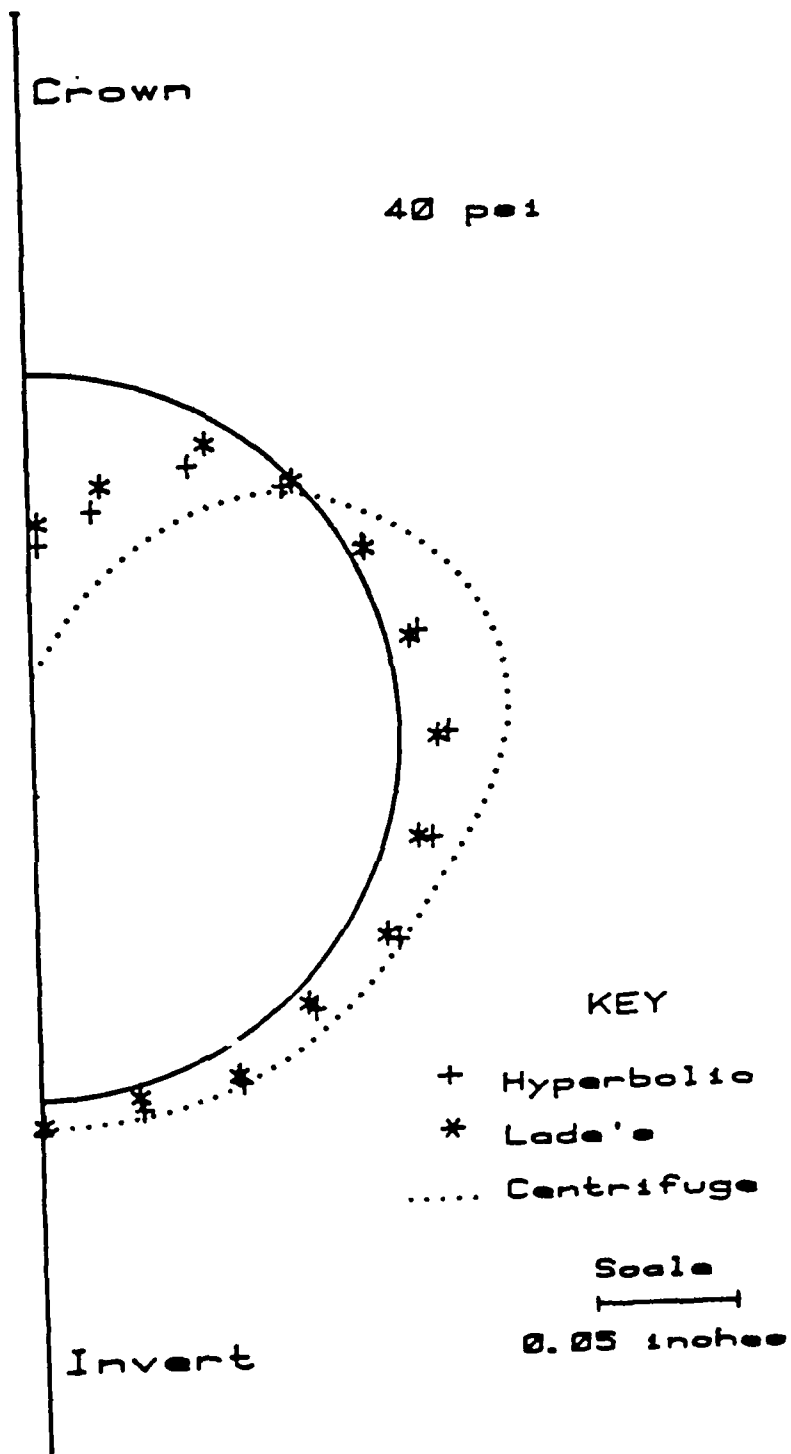


Fig. 10. Deflection of Buried Culvert -- Comparison Between
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